508

Cropping Intensity Impacts on Soil Aggregation and Carbon Sequestration in the Central Great Plains

Maysoon M. Mikha*
Joseph G. Benjamin
Merle F. Vigil
David C. Nielson
USDA-ARS
Central Great Plains Research Station
40335 Co. Rd. GG
Akron, CO 80720

The predominant cropping system in the Central Great Plains is conventional tillage (CT) winter wheat (*Triticum aestivum* L.)–summer fallow. We investigated the effect of 15 yr of cropping intensities, fallow frequencies, and tillage (CT and no-till [NT]) practices on soil organic C (SOC) sequestration, particulate organic matter (POM), and wet aggregate-size distribution. A crop rotation study was initiated in 1990 at Akron, CO, on a silt loam. In 2005, soil samples were collected from the 0- to 5- and 5- to 15-cm depths in permanent grass, native prairie, and cropping intensities (CI) that included winter wheat, corn (*Zea mays* L.), proso millet (*Panicum miliaceum* L.), dry pea (*Pisum sativum* L.), and summer fallow. The native prairie was sampled to provide a reference point for changes in soil parameters. The most intensive crop rotation significantly increased C sequestration compared with the other CIs where fallow occurred once every 2 or 3 yr. Legume presence in the rotation did not improve SOC sequestration relative to summer fallow. Significant amounts of macroaggregates were associated with grass and intensive cropping compared with the rotations that included fallow. Reduced fallow frequency and continuous cropping significantly increased soil POM near the surface compared with NT wheat–fallow. Macroaggregates exhibited a significant positive relationship with SOC and POM. A significant negative correlation was observed between microaggregates and POM, especially at 0- to 5-cm depth. Overall, a positive effect of continuous cropping and NT was observed on macroaggregate formation and stabilization as well as SOC and POM.

Abbreviations: ACR, alternative crop rotation; CI, cropping intensity; CT, conventional tillage; NT, no-till; POM, particulate organic matter; SOC, soil organic carbon; WCF, wheat–corn–fallow; WCM, wheat–corn–millet; WCMF, wheat–corn–millet–fallow; WCMP, wheat–corn–millet–pea; WF, wheat–fallow; WSA, water-stable aggregates.

Losses of SOC in the Great Plains have been associated with tillage and summer fallow management (Bowman et al., 1999; Halvorson et al., 2002a,b). In this region, water is the most limiting factor for crop production. Fallow periods are included in cropping systems to improve soil water storage for subsequent crops. Peterson et al. (1998) pointed out that a fallow period improves the chance of having some available water during grain fill, thereby increasing crop yield; however, a loss of SOC during fallow is likely to occur. Fallow, in any cropping sequence, is a period of microbial activity and residue decomposition with no crop residue input. Consequently, the soil becomes susceptible to wind erosion and SOC loss (Halvorson et al., 2002a).

The combination of wheat–fallow with CT further promotes SOC losses because tillage (i) increases residue mixing with soil and soil aeration, which enhances residue decomposition, (ii) destroys soil aggregates and exposes previously protected SOC to soil fauna, and (iii) increases losses due to soil erosion (Blevins and Frye, 1993; Beare et al., 1994; Paustian et al., 1997). Adopting NT improves the conservation of soil water during the fallow period compared with a CT system

Mention of commercial products and organizations is solely to provide specific information. It does not constitute endorsement by the USDA-ARS over other products and organizations not mentioned. The USDA-ARS is an equal opportunity/affirmative action employer and all agency services are available without discrimination.

Soil Sci. Soc. Am. J. 74:1712–1719
Published online 6 Aug. 2010
doi:10.2136/sssaj2009.0335
Received 4 Sept. 2009.
*Corresponding author (Maysoon.Mikha@ars.usda.gov).

(Nielsen et al., 2005). In addition to increasing soil water conservation, NT increases surface SOC as a result of increased residue accumulation, less residue mixing, less oxidation, less soil disturbance, reduced soil temperature, proliferation of root growth and biological activity, and decreased risks of soil erosion (Blevins and Frye, 1993; Six et al., 1999).

It has been documented that NT soils have improved soil aggregation, C sequestration, and aggregate stability (Mikha and Rice, 2004; McVay et al., 2006; Zhang et al., 2007), which results in increased water infiltration and resistance to wind and water erosion (Zhang et al., 2007). Soil aggregation is one of the important characteristics that mediates many soil chemical, physical, and biological properties and improves soil quality and sustainability. The stability of macroaggregates (>250-μm diam.) is particularly responsive to changes in management practices (Jiao et al., 2006; Zibilske and Bradford, 2007). The loss of macroaggregate-occluded organic matter is a primary source of C and nutrients lost as a result of cultivation (Six et al., 2002; Mikha and Rice 2004; Jiao et al., 2006; Zibilske and Bradford, 2007).

Smika and Wicks (1968) documented that the use of NT in the Central Great Plains improved soil water conservation, which allows decreasing fallow frequency (two crops in 3 yr). Nielsen et al. (2005) also recognized that intensifying a cropping system is possible with NT management in the Great Plains region. Intensive cropping systems with reduced tillage and fewer fallows provide more residues, increase SOC content, and reduced potential for soil erosion (Halvorson et al., 2002a). Reduced fallow frequency with less soil disturbance in an NT system, relative to CT wheat–fallow, can produce more grain per unit of soil water (Nielsen et al., 2005) and leave more residues on the soil surface (Cantero-Martinez et al., 2006). Therefore the possibility for sequestering C in soil increases with intensive cropping systems (Peterson et al., 1998) and NT management.

Previous research in the Great Plains emphasized the effect of different tillage practices and reduced fallow frequency on SOC content (Peterson et al., 1998; Bowman et al., 1999; Halvorson et al., 2002a,b; McVay et al., 2006), crop yield (Halvorson et al., 2002b), and soil chemical properties (Mikha et al., 2006). Recently Benjamin et al. (2008) evaluated the effect of SOC and soil aggregation on soil physical and hydraulic properties, but they were limited to two rotations and grass plots. Very little documentation from long-term studies exists that compares the combined effects of reduced fallow frequency and NT on soil aggregation, aggregate size distribution, and POM. Furthermore, few studies have been reported that have examined the relationship between aggregate size distribution and increasing SOC and POM. Thus, the objectives of this study were to: (i) assess changes in aggregate size distribution, SOC, and POM caused by NT management and by reducing fallow frequencies; and (ii) correlate changes in aggregate size distributions with changes in SOC and POM. This study is different from previous studies because it evaluates the long-term influence of cropping intensity in combination with NT management on soil quality parameters (e.g., soil aggregation, POM, and C sequestration) in the upper 15 cm of the soil in the Central Great Plains.

Table 1. Description of cropping intensity and crop sequence. The phases of each rotation were combined for analysis.

Cropping intensity†	Cropping sequence‡
0.5	WF_{CT}, WF_{NT}
0.67	WCF, CFW, FWC
0.75	WCMF, CMFW, MFWC, FWCM
1.0	WCM, CMW, MWC, WCMP, CMPW, MPWC, PWCM

† The cropping intensity indicates the frequency of fallow in the rotation.
‡ All rotations were in no-till except wheat–fallow, which was studied under no-till (WF_{NT}) and conventional tillage (WF_{CT}); W, winter wheat; F, fallow; C, corn; M, millet; P, pea.

MATERIALS AND METHODS

Site Description

The research plots are located at the USDA-ARS Central Great Plains Research Station (Akron, CO) on the Alternative Crop Rotation (ACR) study site. The study lies at 40.15° N and 103.15° W. The elevation of the station is 1384 m above mean sea level. The research station is within a semiarid climate with approximately 420 mm of annual precipitation. Long-term weather data show that normally about 80% of the annual precipitation occurs between April and September. About 25% of the annual precipitation is received as snow and another 29% occurs as rain in July and August, a critical period for annual summer crop development. The average daily temperature is 9°C, ranging from −2°C in January to 23°C in July. The soil is a Weld silt loam (a fine, smectitic, mesic Aridic Paleustoll). The soil bulk density ranged from 1.30 to 1.50 g cm^{-3} in the 0- to 15-cm depth. Soil texture ranged from 37 to 39% sand, 39 to 41% silt, and 22 to 23% clay in the 0- to 7.5-cm depth.

The ACR plots were initiated in 1990 under various degrees of CI. Rotations of crops suited for dryland crop production in the Central Great Plains are the experimental treatments. Each phase of each rotation was included in each year of the study. The different cropping sequences evaluated in this study are specified in Table 1. The crop rotations were comprised of winter wheat, corn, proso millet, and dry pea, with or without fallow. The crop rotations were compared with perennial grass plots, which were included within the experimental design. A prairie site was also sampled to provide a benchmark reference of soil properties. The experimental plots were under long-term cultivation before the experiment establishment in 1990, whereas the native prairie, surrounding the research plots, has never been cultivated. The experiment is organized as a randomized complete block design with three replications. Because the native prairie was not replicated within the experimental plots, it was excluded from the statistical analysis. One crop was harvested from the wheat–fallow (WF) rotation every 2 yr (0.5 CI); a crop was harvested from the wheat–corn–fallow (WCF) rotations 2 out of 3 yr (0.67 CI); a crop was harvested from the wheat–corn–millet–fallow (WCMF) rotations 3 out of 4 yr (0.75 CI); and a crop was harvested from the wheat–corn–millet (WCM) and the wheat-corn-millet-pea (WCMP) rotations every year (1.0 CI). The perennial grass plots were originally seeded to a mixture of 45% smooth brome (*Bromus inermis* Leyss), 45% pubescent wheatgrass [*Agropyron trichophorum* (Link) K. Richt.], and 10% alfalfa (*Medicago sativa* L.) at the start of the experiment. The alfalfa quickly died, so by the time the samples were taken (2005), the plots were almost exclusively grass. The native prairie site has a mixture of blue grama [*Bouteloua gracilis* (Kunth) Lag. ex Griffiths] and buffalo grass [*Bouteloua dactyloides* (Nutt.) Columbus]. Soil was sampled from the experimental plots, including the grass plots, and from three locations in the prairie site. The three native prairie locations were each within 100 m south, east, and west of the edge of ACR experiment plots. Native prairie samples were included to provide a benchmark reference of soil properties.

No-till management was used on all rotation plots except for the WF rotation, which was managed with both NT (WF_{NT}) and CT (WF_{CT}). The CT for WF rotation included tillage with three to six sweep plow operations approximately 8 to 10 cm deep as needed for weed control during the summer fallow. The plot size (9.1 m by 30.5 m) and machinery working widths were such that the wheel tracks for field operations follow a controlled wheel traffic pattern. The only soil disturbance in untracked areas was from planting operations. In the NT plots, chemical weed control was used during the fallow and cropping seasons. A typical herbicide application scheme consisted of a residual herbicide application of atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] after wheat harvest. A burn-down application of glyphosate [isopropylamine salt of *N*-(phosphonomethyl)glycine] was applied shortly before planting the following crop. Several glyphosate applications were made, as needed, during the fallow period for weed control. Wheat planting occurred in mid to late September of each year of the study. Corn planting occurred in mid to late May. Millet planting occurred in late May or early June. Pea planting occurred in early April. Wheat, millet, and pea were planted with a 0.19-m row spacing and corn was planted with a 0.76-m row spacing. Fertilizer N was applied to each plot according to soil tests obtained each year and the projected crop yield. The N source was NH_4NO_3, broadcast before planting the crop or as a dribble band 7.6 cm to the side of the seed row as a 32% N solution of urea–NH_4NO_3. For wheat only, a starter fertilizer of 11–52–0 (N–P–K) was banded with the seed at planting at a rate of 2.8 kg P ha^{-1}.

Soil samples were taken in March 2005, which was 15 yr after the establishment of the ACR research plots. Samples were also taken from the undisturbed native prairie site. Composite samples consisting of 10 2.5-cm-diam. cores were taken from the 0- to 5- and 5- to 15-cm depths of each treatment using an Oakfield soil probe (Forestry Supplies, Jackson, MS). Soil samples were collected between the rows from each plot. Wheel-trafficked areas were purposely avoided during sampling. Soil samples were placed in sterile polypropylene bags, kept in coolers during field sampling, and stored at 4°C after collection. The field-moist soil samples were presieved (6-mm diam.) before wet sieving to remove stones and coarse organic matter, to homogenize the sample, and to define the initial dimensions for the aggregate analysis. Soil bulk density was determined concurrently from core samples taken at the 0- to 5- and 5- to 15-cm depths of each treatment (Grossman and Reinsch, 2002).

Aggregate Size Distributions

Water-stable aggregates (WSA) were separated using an instrument similar to the modified apparatus used by Mikha et al. (2005). The apparatus was modified and designed to handle stacked sieves (12.7-cm diam.) and to allow complete recovery of all particle fractions from the individual samples. The aggregate size distribution and the sand-free WSA were evaluated using the procedure reported by Mikha and Rice (2004). Aggregates from each treatments were separated into macroaggregate (>1000, 500–1000, and 250–500 μm) and microaggregate (53–250 and 20–53 μm) size fractions.

Particulate Organic Matter

Particulate organic matter was determined using the procedure of Cambardella et al. (2001). Briefly, 30 g of air-dry soil was dispersed in 90 mL of 5% sodium hexametaphosphate. The suspensions were shaken for 16 h on a reciprocal shaker. The dispersed soil was passed through a set of nested sieves having mesh sizes of 1000, 500, 250, and 53 μm, where the material retained on each sieve was rinsed until all materials smaller than the mesh size had been washed through. The material retained on each sieve was transferred into an aluminum weighing pan and dried to a constant weight at 50°C. The dried mass was recorded to the nearest milligram. Loss-on-ignition for POM was determined by the mass difference after 4 h in a muffle furnace at 450°C. The sum of different POM size fractions (total POM) was used to evaluate the effect of different CI and tillage on soil POM content. In addition the individual POM size fractions were used to evaluate the relationship between WSA and POM within the same size class. The POM was calculated as reported by Mikha et al. (2006):

$$\text{g POM kg}^{-1}\text{ soil} = \frac{\begin{matrix}\text{initial mass}\\ \text{of the fraction}\end{matrix} - \begin{matrix}\text{mass of the fraction}\\ \text{after ignition}\end{matrix}}{\text{initial mass of the soil}} \times \frac{1000\text{g}}{\text{kg}} \quad [1]$$

Soil Organic Carbon

Fifteen years after initiation of this study, the soil pH in the plots ranged from 4.3 to 5.82 within the 0- to 5-cm depth and from 5.1 to 6.12 for the 5- to 15-cm depth. Low soil pH (<6) indicates the absence of soil carbonates. Therefore, we considered all C present within the 0- to 15-cm depth of the soils to be organic C. Soil organic C was measured by direct combustion (950°C) using a LECO CHN-2000 (LECO Corp., St. Joseph, MI). Air-dry soils were ground to a fine powder using a roller mill, and about 0.2 g of ground soil was analyzed.

Statistical Analysis

Statistical analysis of cropping system effects on SOC, water-stable macroaggregates, and POM was conducted using ANOVA. The *F*-protected *t*-test was used on pairwise comparisons to follow up any significant findings for each individual depth, 0 to 5 or 5 to 15 cm. The PROC MIXED procedure of SAS Version 8 (SAS Institute, 1999) was used for ANOVA and mean separation differences. All results were considered significantly different at $P < 0.05$ unless noted otherwise. Simple regression models and correlations between SOC and WSA and between WSA and POM were performed across all cropping systems for each individual depth.

RESULTS AND DISCUSSION

Soil Organic Carbon

Cropping intensity significantly affected SOC within the 0- to 5-cm ($P = 0.03$) and 0- to 15-cm ($P = 0.03$) depths (Fig. 1). No significant differences in SOC were observed between

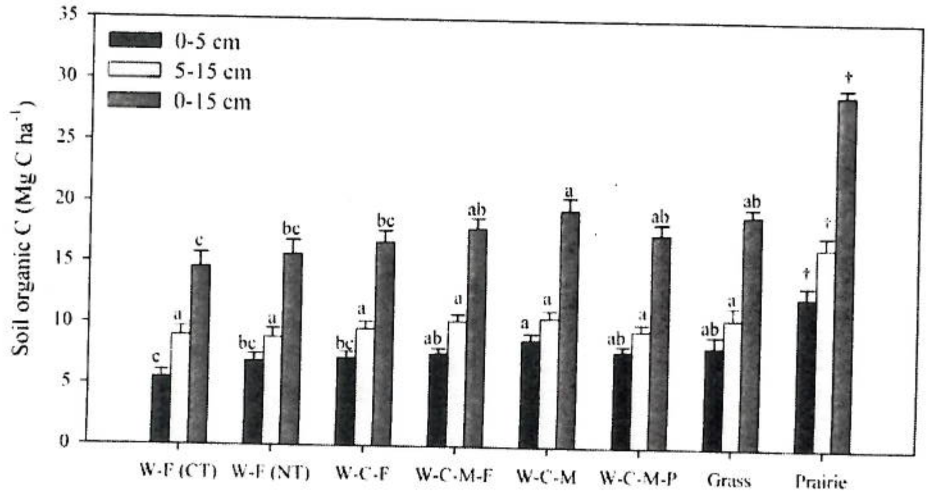

Fig. 1. Soil organic C as affected by different cropping intensities (W, wheat; F, fallow; C, corn; M, millet, P, pea) and tillage (CT, conventional tillage; NT, no-till). Lowercase letters represent significant differences ($P \leq 0.05$) among cropping intensities at the same depth. All phases of each rotation were sampled. The error bars represent standard errors. †Prairie data were not included in the statistical analysis.

the 1.0 CI rotations (WCM and WCMP), the 0.75 CI rotation (WCMF), and the grass plots at the 0- to 5-cm and 0- to 15-cm depths. Similarly, Benjamin et al. (2008) observed no differences in SOC between a WCM rotation and grass plots at the 2- to 9.5-cm depth. Significantly greater amounts of SOC were associated with the fully cropped WCM rotation relative to the 0.5 CI (WF_{NT} and WF_{CT}) and 0.67 CI (WCF) rotations (Fig. 1). No significant differences in SOC were observed between the rotations that included pea (1.0 CI, WCMP) vs. the summer fallow rotations with NT. We assumed that the fast decomposition rate of pea relative to other crops in the rotations results in less SOC accumulation after a pea crop.

The relative differences in SOC (Fig. 1) between the 1.0 CI (WCM rotation), the 0.75 CI (WCMF rotation), and the 0.67 CI (WCF rotation) were similar to the results of Bowman et al. (1999), who also sampled the ACR plots at an earlier date. Bowman et al. (1999) showed that the 1.0 CI retained 17% greater SOC than the 0.75 CI and about 24% greater than the 0.67 CI. Our data showed that SOC in the 1.0 CI was 16% greater than in the 0.75 CI and 22% greater than in the 0.67 CI. Continuous cropping, WCM, retained significantly greater amounts of SOC relative to 0.5 CI, with the other CIs studied having intermediate values. Halvorson et al. (2002b) also reported that including fallow in cropping systems, even with NT management, may result in SOC loss. Similarly, Mikha et al. (2006) reported an increase in SOC within the 0- to 7.5-cm depth resulting from decreased fallow frequency. In general, a loss of SOC is likely to occur during the fallow period (Cihacek and Ulmer, 1995). Fallow signifies a phase of continued microbial activity and residue decomposition with no crop residue input. Also, soil may be more susceptible to SOC loss by wind erosion during the fallow period (Hass et al., 1974). The combination of CT and 0.5 CI (WF_{CT}) retained the lower SOC, within the 0- to 5-cm depth, compared with other CI rotations except WF_{NT} and WCF (Fig. 1). Within the same 0.5 CI rotation, the retention of SOC with WF_{NT} was not significantly different from WF_{CT}. Unlike previous studies (Halvorson et al., 2002a; Beare et al., 1994; McVay et al., 2006; Paustian et al., 1997), the tillage system here was a sweep plow, which minimizes the mixing of crop residues with the soil. The limited mixing appeared to reduce the differences in SOC between the two tillage treatments.

Within the 5- to 15-cm depth, SOC in cropped soil was not significantly affected by CI, grass, or tillage practices (Fig. 1). The significant differences in SOC ($P = 0.03$) among the rotations of various CIs were more pronounced for the composite 0- to 15-cm depth than for the 5- to 15-cm depth. Treatment differences in SOC for the composite 0- to 15-cm depth were the same as those for the 0- to 5-cm depth, which indicates that most of the treatment differences were probably associated with the 0- to 5-cm depth. Using the native prairie sites only as a benchmark for comparing cropped plots to undisturbed prairie, we found that at any depth, SOC sampled from the native prairie sites was at least 39% greater than the highest values measured in the crop rotation experiment. One might speculate if the measured differences are statistically significant or not; which we won't do here. The point is that our measurements of SOC in these rotation and established grass plots is still falling short of what we have measured in the native prairie system just adjacent to this experiment. Given the slow rate of SOC sequestration in this region, cropping systems may never achieve the precultivation conditions (Russell et al., 2005).

Soil Aggregation and Particulate Organic Matter

The aggregate size distribution within the 0- to 5-cm depth was significantly ($P < 0.0001$) influenced by CI and tillage practices (Fig. 2). A similar pattern was observed within the 5- to 15-cm depth (data not shown). Depth had no significant effect on the aggregate size distribution with any CI rotations or grass plots. For the 0.5 CI (WF_{NT} vs. WF_{CT}), the significantly greater amount of soil macroaggregates (>1000-, 500–1000-, and 250–500-μm diam.) associated with WF_{NT} was attributed to tillage elimination. In a Central Great Plains regional study, Blanco-Canqui et al. (2009) also observed greater macroaggregate stability associated with NT than CT. They related the higher stability to reduced macroaggregate wettability and the greater kinetic energy required to disintegrate macroaggregates associated with NT than with CT. Including fallow in the rotation (0.67 and 0.75 CI) significantly reduced the proportion of macroaggregates (250–500 μm) compared with the 1.0 CI rotations (Fig. 2). The fully cropped WCM and WCMP rotations significantly increased the 250- to 500-μm macroaggregates by 32 and 27%, respectively, compared with the 0.67 CI and by 33 and 32%, respectively, compared with the 0.75 CI.

Aggregates in the 53- to 250-μm class comprised the greatest proportion of whole soil, followed by aggregates in the 20- to 53- and 250- to 500-μm classes (Fig. 2). Relatively more macroaggregates (500–1000 and 250–500 μm) were associated with grass than with the crop rotations, with a corresponding decrease in the proportion of microaggregates (20–53 μm) in grass plots relative to crop rotation plots. John et al. (2005) observed a greater proportion of macroaggregates in grassland soil compared with a greater proportion of microaggregates in cropland.

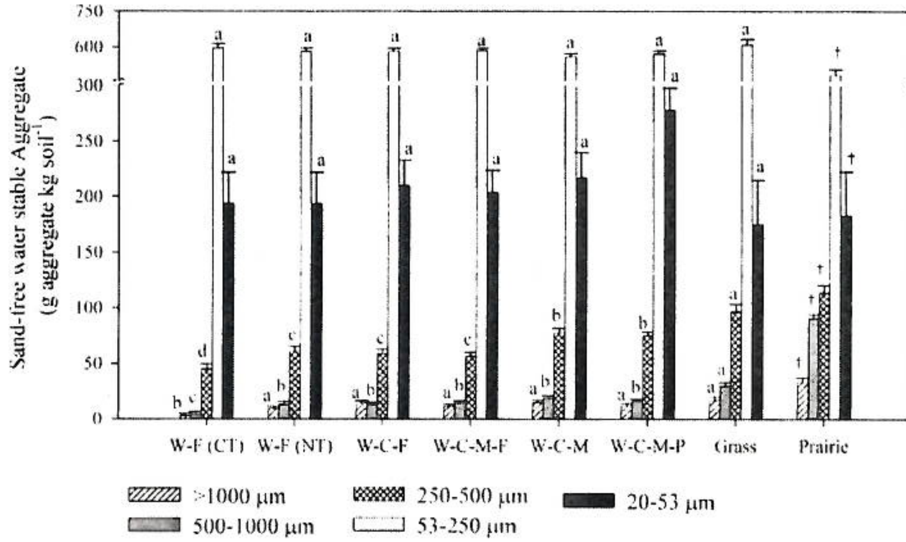

Fig. 2. Sand-free water-stable aggregates in different size fractions within the 0- to 5-cm depth as affected by different cropping intensities (W, wheat; F, fallow; C, corn; M, millet, P, pea) and tillage (CT, conventional tillage; NT, no-till). Lowercase letters represent significant differences ($P \leq 0.05$) among cropping intensities at the same aggregate size fraction. All phases of each rotation were sampled. The error bars represent standard errors. †Prairie data were not included in the statistical analysis.

Soil POM was significantly influenced (Fig. 3) by crop rotations ($P < 0.0005$), depth ($P < 0.0001$), and the two-way interaction crop rotation × depth ($P = 0.0002$). Across the rotations and grass treatments, a greater concentration of POM was associated with the 0- to 5-cm depth than with the 5- to 15-cm depth. The continuous cropping rotation WCM significantly increased soil POM at the 0- to 5-cm depth compared with the other continuous cropping rotation (WCMP) by 17% and continuous grass by 21%. Soil POM associated with 1.0 CI (WCM) was significantly greater than the rotations containing fallow, the 0.50 CI (W-F_{NT}), 0.67 CI (WCF), and 0.75 CI (WCMF) by 53, 29, and 21%, respectively. This indicates that, in general, the differences in soil POM among CI increased as fallow frequency increased in rotations. This observation is consistent with Mikha et al. (2006), who observed an increase in soil POM level with a reduction in tillage intensity and fallow frequency. Numerically, the POM measured in the adjacent reference native prairie sites were 2.4 times greater than the highest values measured in the continuously cropped rotation plots.

Relation between Soil Aggregates, Soil Organic Matter, and Particulate Organic Matter

The correlation between SOC and WSA was affected by depth and aggregate size class (Fig. 4). There was a positive linear correlation (Fig. $4A_1$ and $4A_2$) between SOC and the quantity of soil macroaggregates within both depths studied (0–5 and 5–15 cm), similar to the results of Six et al. (2002) and Jiao et al. (2006). The smaller size macroaggregates (250–500 μm) exhibited a different correlation and slope than the larger macroaggregates (>1000 and 500–1000 μm) at both depths (Fig. $4A_1$ and $4A_2$). For 0- to 5-cm, the slope of the regression line was significantly ($P = 0.04$) greater with the smaller macroaggregates than with the larger size macroaggregates (Fig. $4A_1$). Also, for the same amount of soil organic matter (SOM), the amount and stability of the smaller macroaggregates were significantly greater than for the larger macroaggregates. The greater mass of small macroaggregates (250–500 μm) than larger macroaggregates could partly be due to the disintegration of large macroaggregates (>1000 and 500–1000 μm) induced by slaking. It has been well

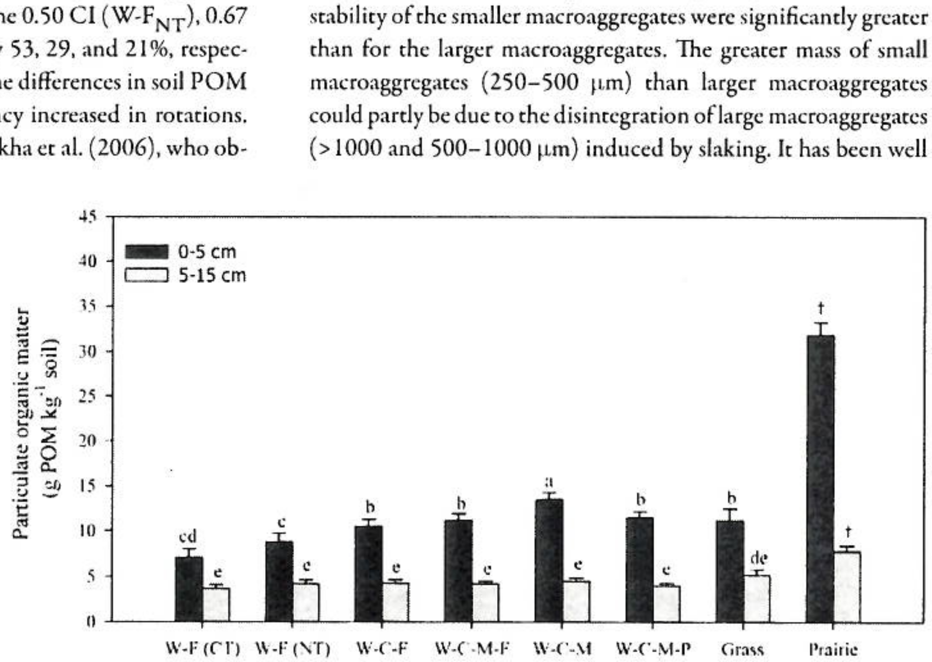

Fig. 3. Total particulate organic matter (POM) content within the 0- to 5- and 5- to 15-cm depths as affected by different cropping intensities (W, wheat; F, fallow; C, corn; M, millet, P, pea) and tillage (CT, conventional tillage; NT, no-till). Soil total POM contents were calculated by the sum of the POM associated with different size classes. Lowercase letters represent significant differences ($P \leq 0.05$) among cropping intensities for the same depth. All phases of each rotation were sampled. The error bars represent standard errors. †Prairie data were not included in the statistical analysis.

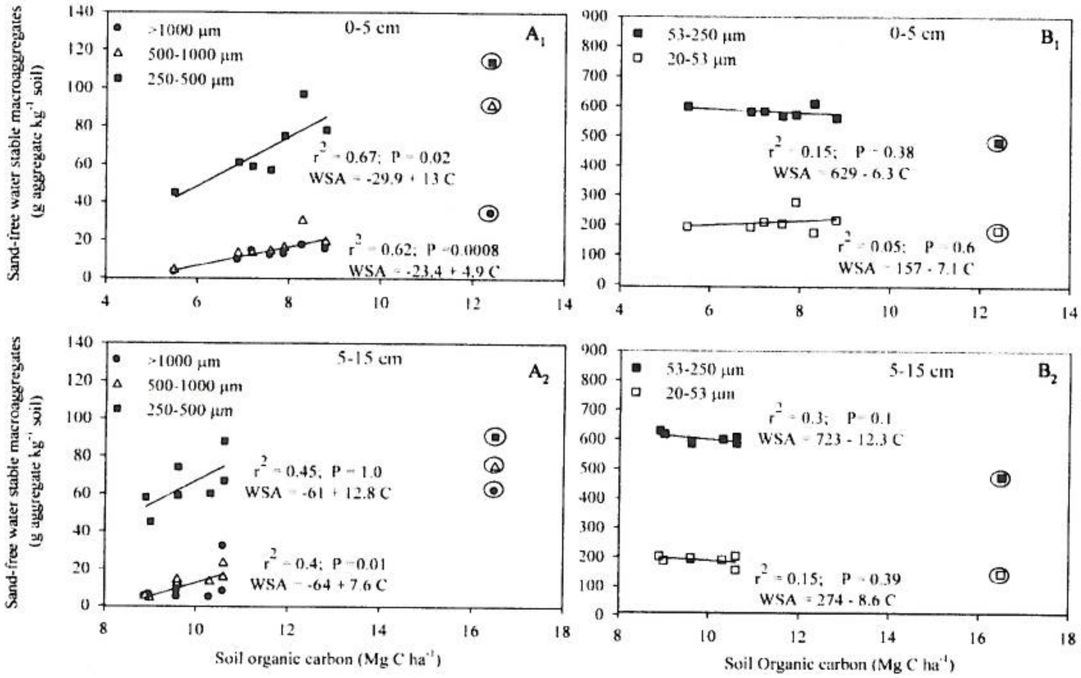

Fig. 4. Relationship between sand-free water-stable aggregates (WSA) and whole-soil organic C (Mg C ha^{-1}) as affected by different cropping intensities and tillage within the 0- to 5-cm depth for (A_1) macroaggregates and (B_1) microaggregates, and the 5- to 15-cm depth for (A_2) macroaggregates and (B_2) microaggregates. The regression lines for A_1 and A_2 group large macroaggregates (>1000 and 500–1000 μm) fractions together for analysis, where different symbols identify each aggregate size class. The symbols that are circled represent the relationship between sand-free WSA and SOC from soils collected at the reference prairie site and are included for reference purposes only. The prairie data were not included in the regression analysis.

documented that some large macroaggregates often consist of clusters of small macroaggregates and microaggregates (Jastrow and Miller, 1997; Six et al., 2000). As the macroaggregates increase in size, they become more susceptible to disintegration due to land use management (Jastrow and Miller, 1997; Six et al., 1999, 2000) and slaking (Tisdall and Oades, 1982). Indeed, as SOC increased, the stability of smaller macroaggregates increased significantly and at a faster rate than the stability of the larger macroaggregates (>1000 and 500–1000 μm). In the 5- to 15-cm layer, the slope of the regression line for the smaller macroaggregates was not significantly different than for the larger macroaggregates (Fig. $4A_2$).

Low coefficients of determination (0.05–0.3) and nonsignificant relationships were observed between SOC and microaggregates (Fig. $4B_1$ and $4B_2$) at both depths. This indicates that the amount of microaggregates measured was not related to the SOC amount. Previously, Oades and Waters (1991), Jastrow and Miller (1997), and Six et al. (2000) reported that macroaggregates are comprised of clusters of microaggregates. Thus, increasing macroaggregate stability with increasing SOM leads to reduced macroaggregate disintegration and increased microaggregate protection within macroaggregates (Oades and Waters, 1991; Jastrow and Miller, 1997; Six et al., 2000). The prairie samples were not included in the regression analysis because the prairie site was not replicated and because the higher SOC values of the prairie samples would have resulted in a discontinuous data set.

To further elucidate the effect of SOM on individual aggregate size fractions as affected by different land management (CI and grassland), the relationship between WSA and POM within the same size class was evaluated (Fig. 5). The relationship between WSA and POM was affected by aggregate size class and soil depth (Fig. 5). Similar to the relationship between SOC and WSA, there appeared to be a positive linear correlation (Fig. 5) between POM and soil macroaggregates (>1000, 500–1000, and 250–500 μm) within both depths studied (0–5 and 5–15 cm). This indicates an increase in soil macroaggregates as the soil POM of the same size class increases. The macroaggregate stability was significantly and highly correlated with POM at the 0- to 5-cm depth but not at the 5- to 15-cm depth. The 0- to 5-cm depth had a greater concentration of POM than the 5- to 15-cm depth and this may explain the stronger relationship. A negative correlation was observed between POM and microaggregates (Fig. 5), which was significant for the 0- to 5-cm depth but not for the 5- to 15-cm depth. The prairie data are included as a reference point for how the relationship between WSA and POM changes with cultivation.

CONCLUSIONS

Fifteen years of continuous cropping significantly increased SOC, soil macroaggregates, and POM relative to the WF_{CT} and to WF_{NT} rotations. The presence of pea in continuous cropping systems did not improve SOC relative to cropping systems that included a fallow period. The significantly greater amount of soil macroaggregates (>1000-, 500–1000-, and 25–500-μm diam.)

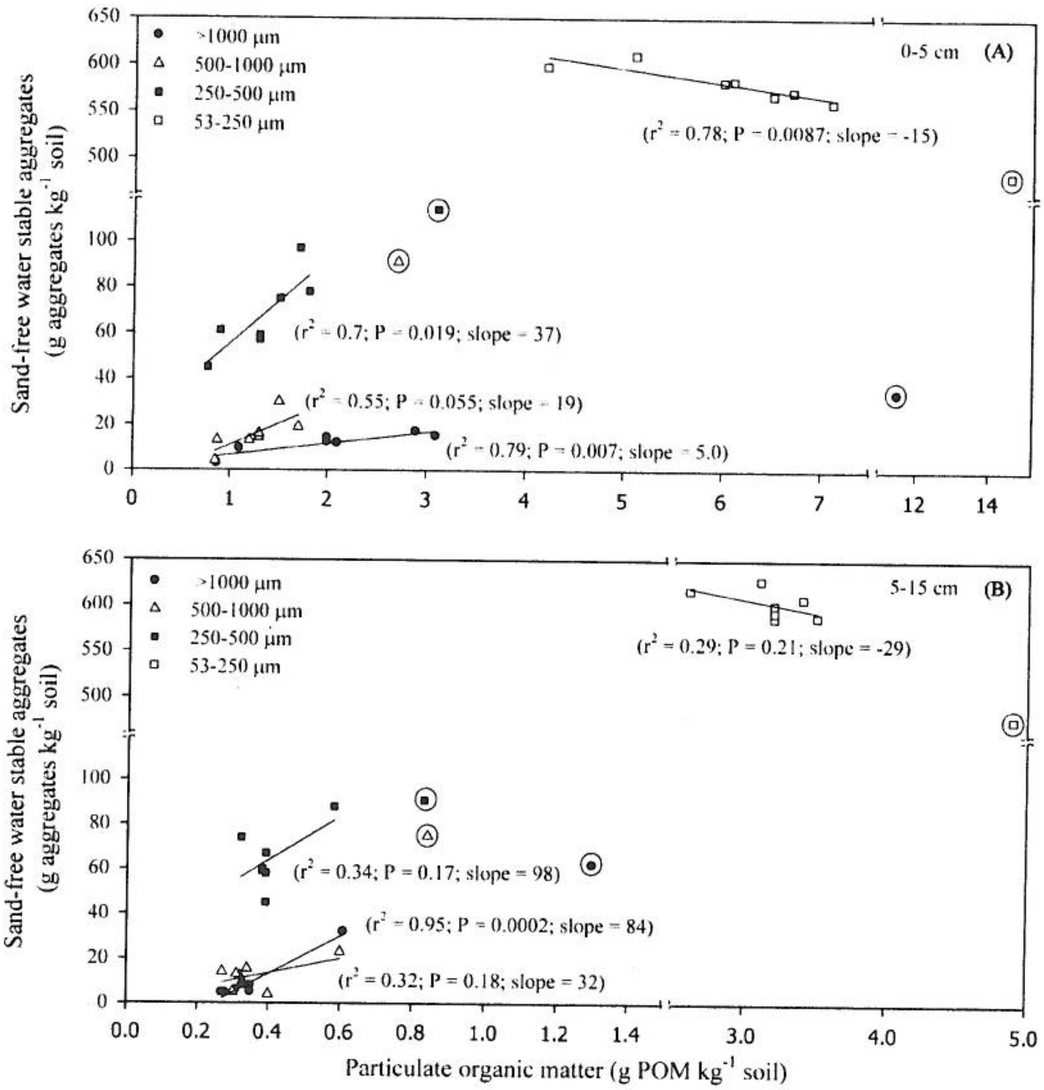

Fig. 5. Relationships between sand-free water-stable aggregates (WSA) and particulate organic matter (POM) are compared within each individual size fraction at (A) 0- to 5- and (B) 5- to 15-cm depths as affected by different cropping intensities and tillage. The circled symbols represent the relationship between sand-free WSA and POM from soils collected at the reference prairie site and are included for reference purposes only. The prairie data were not included in the regression analysis.

associated with WF_{NT} compared with WF_{CT} was a consequence of tillage elimination. Reduced fallow frequency significantly increased soil POM at 0 to 5 cm compared with 0.5 CI (WF_{CT} and WF_{NT}). The fully cropped WCM rotation significantly increased POM, especially within the 0- to 5-cm depth, compared with the other cropping systems and grass. Macroaggregates exhibited a significant, positive relationship with SOC and POM, whereas the microaggregates had a nonsignificant relationship with SOC and POM. Changes in soil properties and SOC in the Central Great Plains appeared to be slow due to the dry conditions and low biomass production. Crop rotations that include a fallow period or tillage promoted SOC losses, thus slowing SOC accumulation and aggregate formation. To improve soil productivity and sustainability, it would be beneficial to identify the most suitable rotations for NT cropping systems in the Central Great Plains.

ACKNOWLEDGMENTS

This publication is based on work supported by the Agricultural Research Service and recently partially supported under the ARS GRACEnet Project.

REFERENCES

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 58:777–786.

Benjamin, J.G., M.M. Mikha, and M.F. Vigil. 2008. Organic carbon effects on soil physical and hydraulic properties in a semiarid climate. Soil Sci. Soc. Am. J. 72:1357–1362.

Blanco-Canqui, H., M.M. Mikha, J.G. Benjamin, L.R. Stone, A.J. Schlegel, D.J. Lyon, M.F. Vigil, and P.W. Stahlman. 2009. Regional study of no-till impacts on near-surface aggregate properties that influence soil erodibility. Soil Sci. Soc. Am. J. 73:1361–1368.

Blevins, R.L., and W.W. Frye. 1993. Conservation tillage: An ecological approach to soil management. Adv. Agron. 51:33–78.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186–191.

Cambardella, C.A., A.M. Gajda, J.W. Doran, B.J. Wienhold, and T.A. Kettler. 2001. Estimation of particulate and total organic matter by weight loss-on-ignition. p. 349–359. *In* R. Lal et al. (ed.). Assessment methods for soil carbon. CRC Press, Boca Raton, FL.

Cantero-Martinez, C., D.G. Westfall, L.A. Sherrod, and G.A. Peterson. 2006. Long-term crop residue dynamics in no-till cropping systems under semi-arid conditions. J. Soil Water Conserv. 61:84–95.

Cihacek, L.J., and M.G. Ulmer. 1995. Estimated soil organic carbon losses from long-term crop–fallow in the northern Great Plains of the USA. p. 85–92. *In* R. Lal et al. (ed.) Soil management and greenhouse effect. Adv. Soil Sci. Ser. CRC Press, Boca Raton, FL.

Grossman, R.B., and T.G. Reinsch. 2002. The solid phase. p. 201–228. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Halvorson, A.D., G.A. Peterson, and C.A. Reule. 2002a. Tillage system and crop rotation effects on dryland crop yield and soil carbon in the Central Great Plains. Agron. J. 94:1429–1436.

Halvorson, A.D., B.J. Wienhold, and A.L. Black. 2002b. Tillage, nitrogen, and cropping systems effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66:906–912.

Hass, H.J., W.O. Willis, and J.J. Bond. 1974. Summer fallow in the northern Great Plains (spring wheat). p. 12–35. *In* Summer fallow in the western United States. Conserv. Res. Rep. 17. U.S. Gov. Print. Office, Washington, DC.

Jastrow, J.D., and R.M. Miller. 1997. Soil aggregate stabilization and carbon sequestration: Feedbacks through organomineral associations. p. 209–223. *In* R. Lal et al. (ed.) Soil processes and carbon cycle. CRC Press, Boca Raton, FL.

Jiao, Y., J.K. Whalen, and W.H. Hendershot. 2006. No-tillage and manure application increase aggregation and improve nutrient retention in a sandy-loam soil. Geoderma 134:24–33.

John, B., T. Yamashita, B. Ludwig, and H. Flessa. 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma 128:63–79.

McVay, K.A., J.A. Budde, K. Fabrizzi, M.M. Mikha, C.W. Rice, A.J. Schlegel, D.E. Peterson, D.W. Sweeney, and C. Thompson. 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Sci. Soc. Am. J. 70:434–438.

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68:809–816.

Mikha, M.M., C.W. Rice, and G.A. Milliken. 2005. Carbon and nitrogen mineralization as affected by drying and wetting cycles. Soil Biol. Biochem. 37:339–347.

Mikha, M.M., M.F. Vigil, M.A. Liebig, R.A. Bowman, B. McConkey, E.J. Deibert, and J.L. Pikul, Jr. 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renewable Agric. Food Syst. 21:26–35.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97:364–372.

Oades, J.M., and A.G. Waters. 1991. Aggregate hierarchy in soil. Aust. J. Soil Res. 29:815–828.

Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls on soil carbon. p. 15–49. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage Res. 47:207–218.

Russell, A.E., D.A. Laird, T.B. Parkin, and A.P. Mallarino. 2005. Impact of nitrogen fertilization and cropping system on carbon sequestration in midwestern Mollisols. Soil Sci. Soc. Am. J. 69:413–422.

SAS Institute. 1999. SAS/STAT user's guide, Version 8. SAS Inst., Cary, NC.

Six, J., E.T. Elliott, and K. Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63:1350–1358.

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099–2103.

Six, J., C. Feller, K. Denef, S.M. Ogle, J.C. Moraes Sa, and A. Alerecht. 2002. Soil organic matter, biota and aggregation in temperate and tropical soils: Effects of no-tillage. Agronomie 22:755–775.

Smika, D.E., and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32:591–595.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soil. J. Soil Sci. 33:141–161.

Zhang, G.S., K.Y. Chan, A. Oates, D.P. Heenan, and G.B. Huang. 2007. Relationship between soil structure and runoff/soil loss after 24 years of conventional tillage. Soil Tillage Res. 92:122–128.

Zibilske, L.M., and J.M. Bradford. 2007. Soil aggregation, aggregate carbon and nitrogen, and moisture retention induced by conservation tillage. Soil Sci. Soc. Am. J. 71:793–802.